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Morphodynamics of deltaic wetlands and implications for coastal ecosystems – A case study of Save River Delta, Mozambique

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ABSTRACT

Deltaic wetlands experience changes over time, with substantial impacts on the coastal ecosystems. These changes, whether they are natural or human-induced, are caused by multiple factors through complex links and interdependences, and constitute challenges for coastal management aiming to set up practical adaptation measures. In this study, we investigate a case study of Save River Delta to interpret the typical morphodynamic pattern on the deltaic plain over an interdecadal timescale and the implications of geomorphological changes for the coastal ecosystems, with emphasis on mangroves. Our results reveal the pattern of the geomorphological changes on the deltaic wetland in river and back-barrier sectors. In both sectors, erosion and accretion are mutually adjusting processes, and they result in geomorphological settings characterized by a distinctive interaction with the ecosystem; on the one hand, mangrove trees colonize new favorable settings; on the other hand, the existing mangrove trees undergo degradation related to the morphodynamic processes. Notwithstanding current episodic events that affect the deltaic wetlands (e.g. cyclones and floods), the changes observed in the study area are part of interdecadal timescale morphodynamics. These changes were consistent for the 50-year time period analyzed. If, on the one hand, some of the episodic and high magnitude weather events such as floods undermine the status of the deltaic ecosystem, on the other hand these events contribute to develop the same ecosystem over a longer timescale. Within interdecadal timescales, biogeomorphological changes in deltaic wetlands are a critical reference frame for understanding future scenarios of environmental changes caused by climate change.
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1. Introduction

Coastal landscape dynamics affect coastal ecosystems (Phillips, 1995; Viles et al., 2008). Coastal wetlands, particularly mangrove, experience natural and human-induced pressures, with visible impacts (Hartig et al., 2002; Day et al., 2008; Ren et al., 2011). Considerable mangrove wetland areas have been lost and degraded over the last decades, and predictions show an increasing scenario of coastal wetland loss (Nicholls et al., 1999; Valiela et al., 2001; Alongi, 2002). Deltaic wetlands, for example, are today supplied with lesser amount of sediment from upstream rivers owing to damming and erosion control along riverbanks, and experience compaction of previously deposited sediments (Syvitski et al., 2009). This contributes to a relative sea-level rise (Törnqvist et al., 2008; van Asselen et al., 2009). Other studies show that parts of the mangrove wetlands are being transformed by aquaculture (Pattanaik and Prasad, 2011; Rahman et al., 2013) which negatively affects the functionality of the natural ecosystem.

Ecosystem change in landscapes is interpreted at different spatial and temporal scales (Lugo, 1980; Berger et al., 2008). At millennial timescales, geologists have inferred climatic and substratum factors that control the development of wetlands over wider spatial scales (Woodroffe et al., 1985; Roberts, 1997; Tanabe, 2003; Berger et al., 2008). Dahdouh-Guebas and Koedam (2008) describe a number of methods that are applied to reconstruct the mangrove ecosystems over multiple spatial and temporal scales. For an interdecadal timescale, remote sensing data have commonly been used to assess mangrove wetland changes (Ozesmi and Bauer, 2002; Dahdouh-Guebas and Koedam, 2008; Pattanaik and Prasad, 2011; Rahman et al., 2013). The results from these studies have been systematically integrated into our current understanding of landscape development and used to produce conceptual and numerical models that explain the current ecosystem succession in the landscape (D'Alpaos et al., 2006; Craft et al., 2009; Mazda and Wolanski, 2009). However, some data are made available in inappropriate formats, posing challenges for environmental modeling.

To bridge the gaps between disciplines and to explain the interaction between biotic and geomorphological processes, the concept of *Biogeomorphology* has emerged (Phillips, 1995; Haussmann, 2011). The concept was explored already by Thom (1967) in his study on a

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deltaic ecosystem in Tabasco, Mexico. Thom (1967) showed evidence of a strong interdependence between the mangrove ecosystem and the different habitats defined by geomorphological units and morphodynamic processes. Other examples of a geomorphologically based approach to explain mangrove development have been presented by Woodroffe (1982, 1992) and Friedrichs and Perry (2001). From these studies, it has become clear that the ecological change in deltaic wetlands depends on a number of factors, some of them controlled by geomorphological and sedimentological processes. However, what remain ambiguous are the patterns over which the changes take place in the landscape in relation to their driving factors. Such patterns are anticipated to be used as a reference frame against which to interpret rapid changes caused by, for example, climate-related events and anthropogenic activities.

In this study we use the example of the Save River delta to understand the morphodynamic processes of deltaic wetlands. The Save River delta and its catchment are unique as they show minimal influence of human activities in comparison with other tropical deltas with mangrove ecosystems (Stanley and Warne, 1998; Blum and Roberts, 2009; Massuanganhe et al., 2015; Macamo et al., 2016). This study aims to: (1) map landscape changes in the deltaic wetland of Save River over the last 50 years; (2) interpret and correlate the changes with their causal processes, and (3) discuss the role of the biota as a feedback to the morphodynamic processes.

2. Biogeomorphology of deltaic wetlands

Deltaic wetlands are located at the interface between fluvial and coastal processes and they are highly susceptible to the combined effects of currents, tides and waves (Jones et al., 2003). In fact, their shape and evolution reflect the prevailing hydrodynamic conditions associated with sediment availability. Feedback of the biota to the sedimentation process has been documented and recognized as a substantial factor in landscape development (e.g. Cowles, 1899; Cooper, 1913; Whittaker, 1953; Phillips, 1995; Naylor et al., 2002). However, only recently have the reciprocal interactions between geomorphology and ecology been structured and discussed (Phillips, 1995; Naylor et al., 2002; Wolanski et al., 2004; Stallins, 2006). With the progress in both fields, accompanied by development and innovations on statistical and numerical modeling platforms, more convincing evidence has been produced showing the interdependences at different scales and in different environments (D'Alpaos et al., 2006; Mazda and Wolanski, 2009; van Asselen et al., 2009). Within these studies, coastal wetlands are highly represented when compared with other landscapes (Day et al., 2008; Corenblit et al., 2011, 2015; Nolte et al., 2013; Escapa et al., 2015).

Mangrove ecosystems are generally assessed from the status of their flora, by which in turn the state of the whole ecosystem is interpreted. Mangrove plants develop under specific conditions of e.g. temperature, salinity, oxygen, soil conductivity, and pH (Kathiresan and Bingham, 2001; Gilman et al., 2008). The plants extract most of their nutrients from the soil where also a benthic fauna develops. One of the interactive mechanisms within the mangrove ecosystem is the bioturbation promoted by sesarmid crabs, gastropods, oysters and worms. These activities result in burrows through which the circulating water replenishes the entire habitat with nutrients and optimizes other essential parameters needed for mangrove development (Ridd, 1996; Skelton and Allaway, 1996; Wolanski et al., 2001; Xin et al., 2009; Stieglitz et al., 2013). In addition, the activities of the benthic fauna promote the stability of the substratum through oxidation and other geochemical interactions (Smith III et al., 1991; Ferreira et al., 2007). Likewise, the roots from mangrove trees trap finer sediments by lowering the water velocity (Augustinus, 1995; Furukawa and Wolanski, 1996; Janssen-Stelder et al., 2002). At this scale, the activities of the mangrove ecosystem contribute to stabilize the sediments and reduce the effect of erosion.

Over a longer time perspective, the average effect of the parameters that regulate the individual development of biotic elements of the wetland tends to vary between different sectors of the mangrove wetland. For an interdecadal time interval, for example, the salinity average tends to be high in the distal sector of the deltaic wetland and low in the proximal sector (Chindah, 2004). Lower salinity is also expected in environmental settings regularly supplied by river water. The averaged parameters regulate the development, survival and adaptation capacity that each biotic component will experience over time. This is likely one of the ways in which natural habitats are formed in many coastal ecosystems (Riley and Kent, 1999).

Different deltaic wetland habitats are formed in diverse sub-environments, which are characterized by specific ecosystem driving factors (Thom, 1967; Thom et al., 1975). In response to the specific conditions, the mangrove ecosystem adapts and certain mangrove species are favored. The habitats are correlated with typical geomorphological features of the delta plain (Thom, 1967; Thom et al., 1975; Woodroffe, 1982, 1992; Augustinus, 1995). Therefore, at the scale of the delta plain, the different habitats stand as components of the whole delta in a similar way that the geomorphological features do. From a geomorphological point of view, the features that compose the deltaic wetland are formed by sedimentary processes that can be mapped (Thom, 1967; Woodroffe, 1992) and interpreted. This process-based capability qualifies the discipline of geomorphology as critical for interdisciplinary studies in deltaic wetlands.

3. Study area

The study area is the wetland located in the lower deltaic plain of Save River, in south-central Mozambique (Fig. 1). The wetland contains a mangrove forest that flourishes discontinuously in approximately half of the whole wetland area, especially in areas with high water exchange close to the two main distributary channels (Matasse Channel and Macau Channel) and smaller inter-distributaries. The mangrove species observed in the study area are dominated by *Rhizophora mucronata*, *Xylocarpus granatum* and *Ceriops tagal* (Macamo et al., 2016). For detailed analysis in this study, we considered the area within the dashed rectangle in Fig. 1C. Most of the selected area is characterized by a muddy substratum and coastal dunes. Alluvial deposits follow adjacently the main river channel in the proximal sector of the delta plain, and cover in part the wetland deposits. The coastal dunes and alluvial deposits are covered by terrestrial vegetation that contributes to their stabilization.

Sea level data for the study area are not available owing to the lack of gauges. However, downscaled projections by INGC (2009) indicate a rising sea level of 45 cm until 2100 for this region. For a longer time perspective, sea-level trends for the study area are interpreted using geological records from South Africa (Ramsay, 1995; Ramsay and Cooper, 2002). The records infer that the sea level may have stabilized 1000 years BP. The study area is within Mozambique Basin, a sedimentary basin that evolved as a result of fragmentation of Gondwana and the subsequent continental drift (Salman and Abdula, 1995; Mahanjane, 2012; Said et al., 2015). The fragmentation was characterized by normal faults that created suitable conditions to accommodate sediments. The geotectonic history of this setting could result in possible sinking if the normal faults are reactivated. However, there are no records of possible changes related to tectonic activities in the study area.

The shoreline is dominated by an oblique wave pattern that induces a northward longshore drift. The waves have significant influence on the morphodynamics of the shoreline in this region (e.g. Massuanganhe and Arnberg, 2008). Episodically, the shoreline processes are disturbed by tropical cyclones and storms that cause changes in the landscape, with particular emphasis to mangrove dieback (Menomussanga and Matavel, 2011; INGC, 2009; Massuanganhe et al., 2015). Three major cyclones have made landfall in the study area over the last 15 years: Eline in 2000, Japhet in 2003 and Favio in 2007. Floods occur seasonally

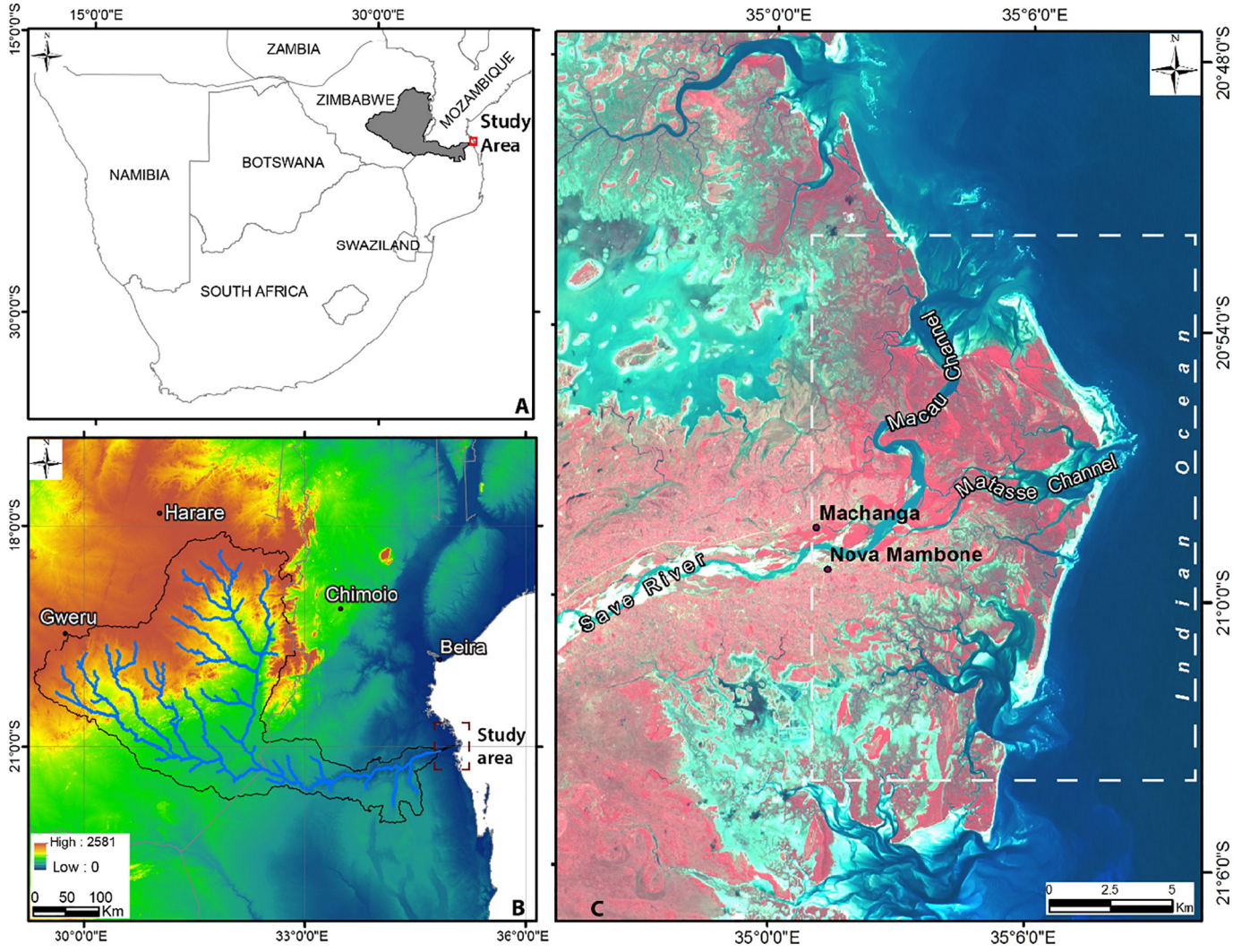

Fig. 1. A - Geographic location of the study area; B – SRTM digital elevation model overlapped by Save River basin and drainage system; and C - SPOT image from 2011, displayed in the typical Red-Green-Blue (RGB) combination showing the physiographic characteristics of the area. On the SPOT image there is a dashed rectangle that shows the area selected for further statistical analysis in GIS.

in the wetland area associated with the river discharge and storm surges that tend to raise sea level temporarily.

The wetland ecosystem represents a valuable natural resource to the population living in nearby Nova Mambone and Machanga villages. People frequent the wetland for fishing and timber collection for household purposes. Currently, there is no commercial exploitation of the mangrove timber, as opposed to other East African and global mangrove areas.

The river catchment covers approximately 102,000 km^2. The largest part is located in Zimbabwe (Fig. 1) where it drains important geological units, including the Zimbabwe Craton. In Zimbabwe, the northern part of the basin is dominated by mountain climate conditions with average precipitation varying between 800 and 900 mm/year. The southern part of the basin is dominated by drier climate with precipitation of approximately 550 mm/year (Waylen and Henworth, 1996). In Mozambique, the basin covers an area dominated by humid and tropical climate with average precipitation ranging between 600 and 750 mm/year (Ramoeli, 2002). The river has a total runoff average of 7000 Mm^3/year (Ramoeli, 2002). The Save River catchment has a few minor dams, located in Zimbabwean tributary rivers. These have limited influence on the river discharge.

4. Methods and data

We used historical aerial photos taken in 1963/4 and four time-series SPOT images taken in 1999, 2007, 2011 and 2014 to produce physiographic maps showing the biogeomorphological attributes of the deltaic wetland. The maps were subsequently compared for detecting changes. These changes were integrated with field data and discussed within the perspective of morphodynamics and evolution processes.

4.1. Geo-referencing and geometric corrections

The SPOT images were projected to Universal Transverse Mercator (UTM), zone 36 S, on WGS84 datum. All images were spatially shifted except the one from 2014, and the SPOT image from 1999 lacked spatial scale. Hence, spatial adjustment was undertaken using ground control points and Google Earth images (cf. Chang et al., 2009; Visser et al., 2014). The image from 1999 was orthorectified applying 20 control points, spatially distributed over the whole scene. The aerial photos were digitized and geo-referenced one by one, tying common points with the already geo-referenced SPOT images. The process was carried

out considering the static features and objects, and we applied between 10 and 30 tying points for each aerial photo. Examples of features and objects used for the geo-referencing are crossroads, buildings, ancient trees and stabilized geomorphologic features (Bitelli and Gatta, 2012).

4.2. Image classification and mapping

The geo-referenced and corrected aerial photos and satellite images were processed in a GIS environment to generate multi-temporal physiographic maps. The aerial photos were interpreted using stereoscope to explore the 3-dimensional view of the features. A vector map was generated based on the mosaic of the aerial photos using ArcGIS 10.2. The basic attribute content of the vector map consists of the main physiographic units that compose the deltaic wetland, with emphasis to the mangrove habitat and coastal dunes. These attributes were compared with the photo-interpretation under stereoscope using a visual approach. Lastly, the vector map was converted to raster.

Each SPOT image was submitted to unsupervised classification into 15 classes using ENVI 5.2. These classes were systematically grouped to outline water, wetland and the mainland (e.g. Massuanganhe and Arnberg, 2008). First the lower spectral reflectance classes were grouped and reclassified as water. Then the intermediate spectral reflectance classes were grouped and reclassified as mangrove wetland. The other spectral reflectance was part of the upper part of the delta. The mapping was partially supervised by comparing the identified classes with the visual interpretation. All the maps were overlapped in GIS environment and manipulated to detect changes between the successive ones. The data were then exported to vector maps and processed in ArcGIS for further statistical analysis and visualization.

4.3. Fieldwork

For this study we undertook field descriptions in multiple campaigns between 2011 and 2015, aiming to assess the ongoing morphodynamic patterns mapped and calculated during the mapping process. By visiting the study area during multiple fieldtrips, we were able to empirically monitor physiographic transformations taking place in some sectors of the delta. The geomorphological and ecological aspects of the study area were described based on visual interpretation, and taking into account the preliminary results from the aerial photo interpretation as well as the environmental factors and disturbances affecting the area. As part of the ground-truthing, we ensured that the physiographic features mapped in the desk study were properly interpreted. Ground observation of sedimentary structures and morphological pattern of specific features were enough to validate the terminology used on the map. Particular attention was paid to the mangrove distribution in the wetland. Some sectors of the study area were visited multiple times, aiming to assess and document possible changes and biogeomorphological interactions.

5. Results

The lower deltaic plain of Save River is characterized by mangrove forest distributed in different habitats that are controlled by geomorphological conditions. The mangrove forest flourishes in recently formed geomorphological features with a high level of water exchange, e.g. point bars and bays (Fig. 2). Conversely, sectors with low water exchange are characterized by scattered mangrove, and occasionally, these sectors are covered by grass. Successive stabilized sand dunes enclose former bays and lagoons. Topographically, the wetland area is situated in intertidal flats, and during flood tide the wetland is progressively flooded, evidencing the general shoreward gentle slope. Tidal channels with different densities drain part of the wetland.

In Fig. 3, we present maps showing changes in the study area over the last 50 years. Specifically, the maps emphasize the successive stages of the deltaic wetland. Considerable changes were registered along the river channel and in the mouth of the river channels (Fig. 3). These changes were greater in the period between 1963/4–1999 (Fig. 3A) than any other subsequent time period in analysis. From 1963/4 to 1999, approximately 1200 ha of wetland area were formed and approximately 600 ha were degraded (Figs. 4, 5) or replaced by coastal dunes. From a geomorphological perspective the changes follow a common erosional and depositional pattern of deltaic environments. In 1963/4 the Matasse Channel consisted of an interconnected channel system composed of two main channels. These channels were progressively accreted with fine sediments over time, and a major accretion is evident between 1963/4 and 1999. In the Macau Channel accretion occurred in point bars and erosion in cut banks (Fig. 3). The tidal channels show changes but at a smaller rate when compared with the ones taking place within the main river distributaries. The deposited sediments in the sector of tidal channels are dominantly fine-grained and rich in organic material. Their thickness varies along the accreted area depending on depositional processes and also on the pre-depositional morphology. Mangrove trees gradually colonize the accreted areas while the benthic fauna initiates its burrowing activities. The erosion observed in the channels acts with intensity in the cut banks, often located in pre-stabilized mudflats, and result in their collapse and consequent degradation of the associated habitat. The combination of erosion and sedimentation in the river channels represents a rejuvenation of the mangrove habitat, where on the one hand the older habitats are eroded and on the other hand new habitats are formed.

In 1963/4, the physiography of the mouths of the distributary channels was characterized by shallow water, part of the deltaic platform. It is on this surface that morphodynamic processes created conditions for new mangrove area. The sedimentation and the ensuing colonization by mangrove occurred progressively and the mangrove occupied first the adjacent sectors of the pre-established wetland. This pattern reflects the interaction between the expanding mangrove ecosystem and the sedimentation processes. In the shoreface, longshore currents and waves have modified the beach and dunes, and affected the mangrove wetland. Over time, coastal processes have eroded previously stabilized dunes and mangrove wetlands, resulting in a decrease of the wetland area. Moreover, the prevailing SE winds have transported dune sand landward and covered part of the back-barrier wetlands, resulting in an additional decrease of the wetland area. In the sector between the mouths of the two main river distributaries there has been a considerable growth of mangrove wetland favored by the development of a spit (Fig. 3A). The incipient spit mapped in 1963/4, developed into a longer one in response to the prevailing SE wind pattern and the resulting longshore drift. While longshore currents move the sediments northwards, the offshore winds have shifted the spit landward. As the spit has grown, a bay has formed, sedimentation of fine particles has occurred, and mangrove has colonized the bay. The landward shift of the spit covered the pre-existing back-barrier wetland causing mangrove degradation as evidenced by a muddy substratum with dead mangrove stems exposed on the shoreface (Fig. 4).

Some sectors in the back-barrier wetland show a dune sand layer with a washover pattern on its surface. The sand has been largely removed from the sheltering dune during episodic high energy events and dispersed in the wetland area, negatively affecting the mangrove ecosystem. The direct impacts of these processes include changes of the ground conditions where the typical mud-dwelling biota is located. This is one of the processes in which the dune sand progressively replaces the deltaic wetland.

The accretion and retreat of the wetland area occurred at different rates over the time in the analysis. Between 1963/4 and 1999 the wetland area expanded at a rate of 35 ha/year. This rate increased gradually in the subsequent time intervals (Fig. 5). Over the time intervals (in the analysis) between 1963/4 and 2011 the wetland retreat rate has increased continuously. This rate has decreased in the time period between 2011 and 2014. Other relevant information to extract from Fig. 5 is the rate of wetland expansion which is higher than the wetland

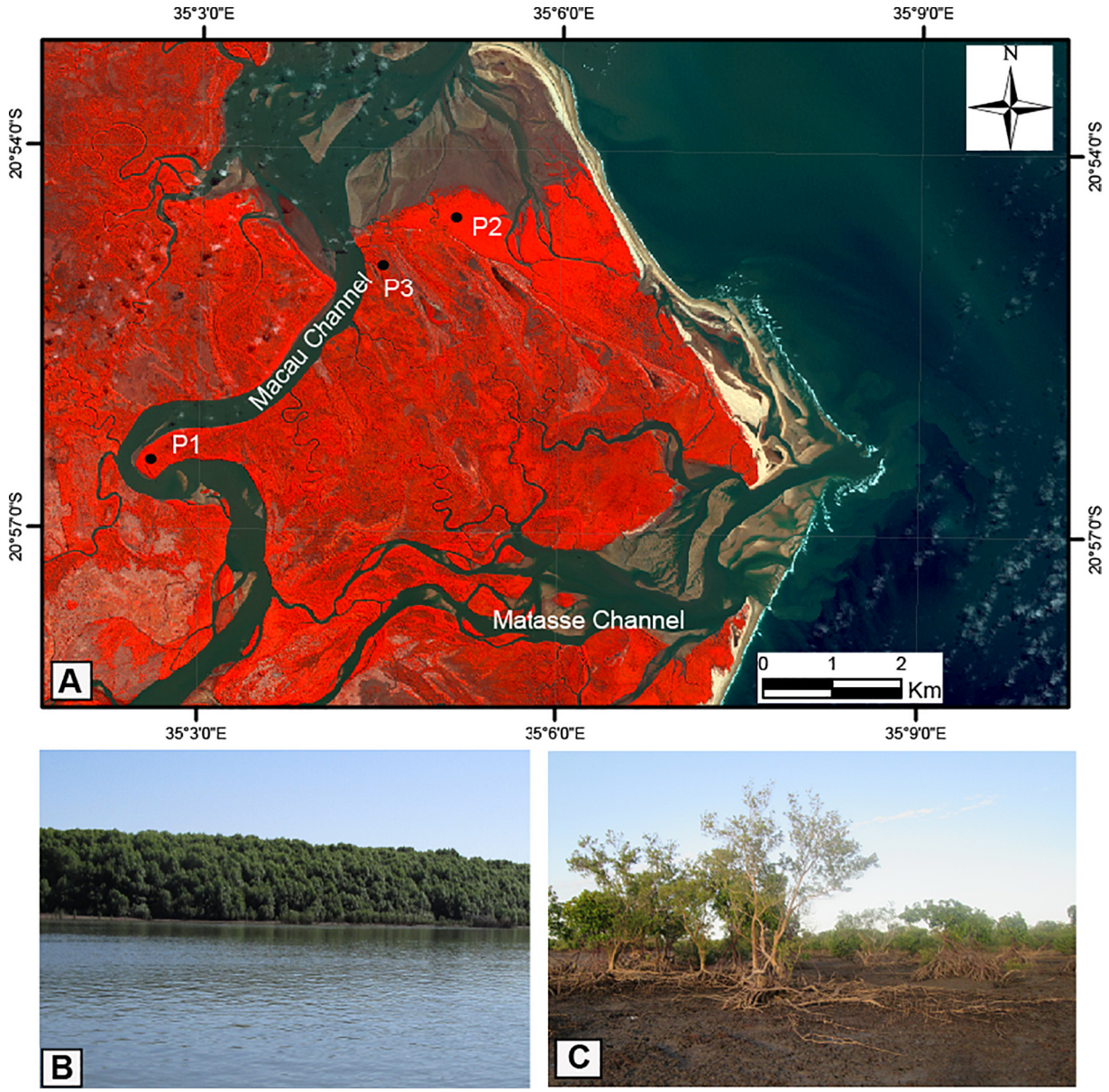

Fig. 2. A - SPOT image from 2014, displayed in the typical Red-Green-Blue (RGB) combination. In the image, the deep red colour shows areas with flourishing mangrove, for example, at P1 and P2; B – photo showing flourishing mangrove in a point bar by Macau Channel (P1); and C – photo showing areas with scattered mangrove trees, such as in the example of P3.

retreat for the period between 1963/4 and 2011. This can be interpreted as a net expansion of wetland area during this period.

In Table 1 we present the accreted and retreated areas for the time intervals in the analysis. There is a general decreasing trend of mangrove area expansion over time. The large area accreted and eroded in the time period 1963/4–1999 is explained by the long time period (36 years) in which the changes were taking place. The total area gained during the time over the analysis period corresponds to the difference between the accreted wetland area and the retreated wetland area. These values show the same trend of decreasing over time but particularly a negative balance in the last time interval in the analysis period.

6. Discussion

The morphodynamics of the deltaic wetland of the Save River over the last 50 years can be interpreted as part of the geomorphological evolution process. The shoreward protruding shape of the deltaic wetland, almost symmetrically divided by Matasse Channel, suggests that this channel previously has been the dominant distributary of Save River. During this stage, the river might have delivered sediments to the shore through this distributary channel, and contributed to the progradation of the delta. This interpretation is supported by the description of the study area by Phipson-Wybrants (1883) that shows the Matasse Channel as the main channel of the delta. At some time during the early 20th century the Matasse Channel avulsed, as evidenced by its reduced width, and part of the water flow was redirected through Macau Channel. We interpret the avulsion of Matasse Channel as a natural process as there are no records of significant human influences in the study area or even in the catchment area. The avulsion may have been caused by excessive sediment load associated with floods, such as described by, for example, Mohrig et al. (2000), Slingerland and Smith (2004) and Hajek and Wolinsky (2012). The aggradational avulsion of Matasse Channel has led to sedimentation of mud under shallow water conditions, and the subsequent increase of the mangrove wetland area mainly during the period between 1963/4 and 2011.

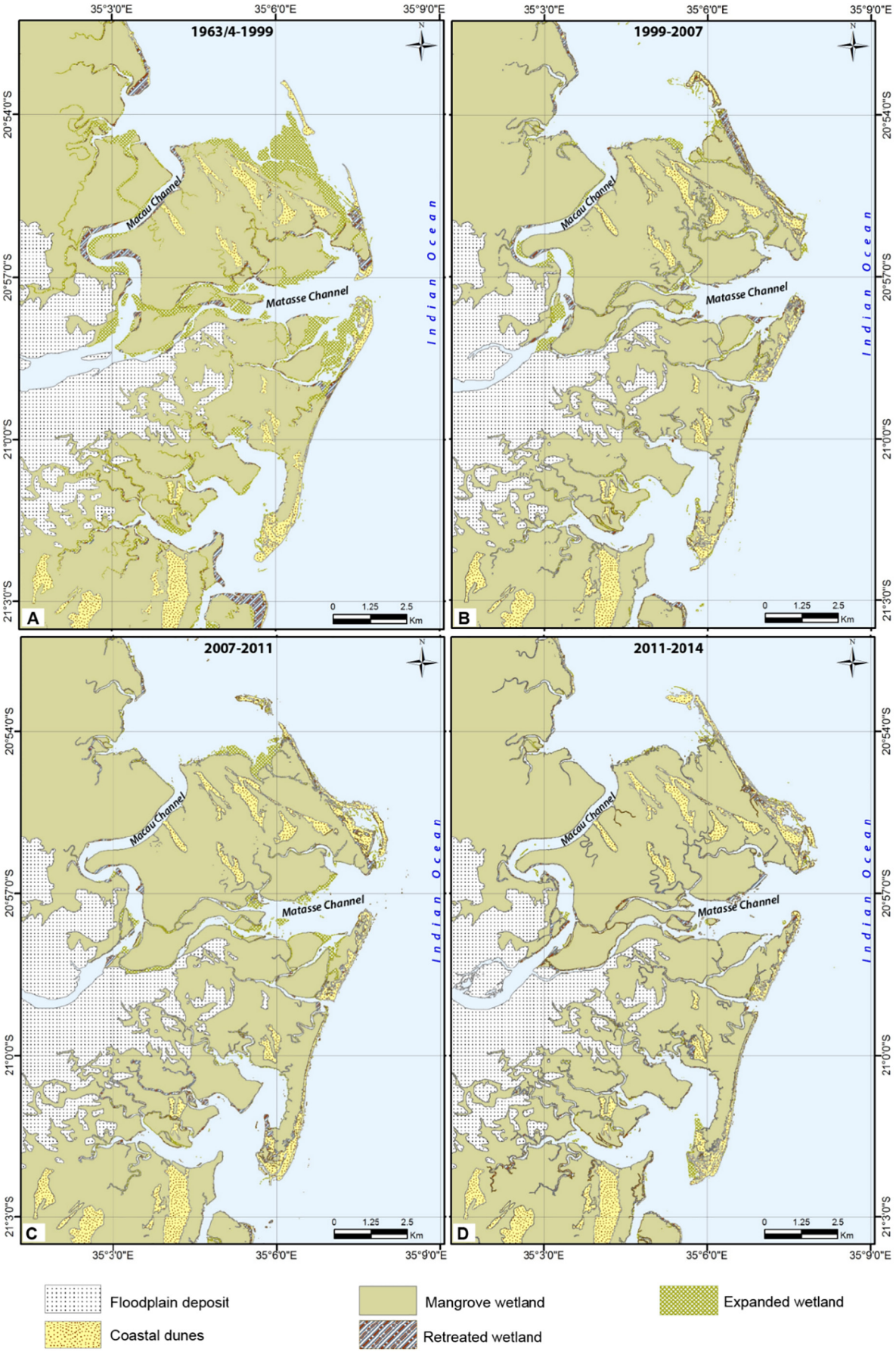

Fig. 3. Physiographic maps showing changes in the wetland area of Save River delta plain during 50 years divided in different time intervals: A – From 1963/4 to 1999 (36 years); B – From 1999 to 2007 (8 years); C – From 2007 to 2011 (4 years); and D – from 2011 to 2014 (3 years). The changes in the maps are expressed as expanded or retreated wetland.

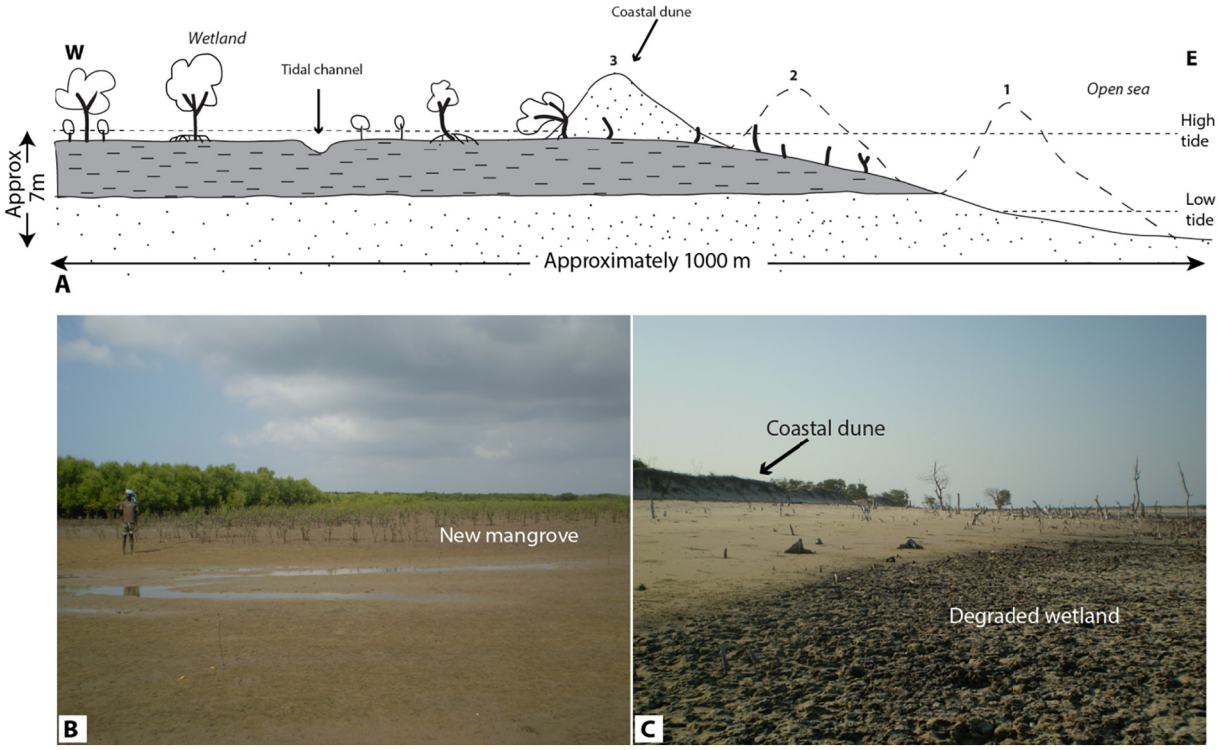

Fig. 4. Diagramatic representation of morphodynamic processes taking place at the distal sector of Save River delta, between the mouths of Macau and Matasse channels; A – schematic representation of coastal dunes shifting landward and covering the mangrove wetland; B – photo showing mangrove expanding as the accumulation of mud takes place, sheltered by coastal dunes from open sea; and C – photo showing muddy substratum and dead mangrove stems reflecting the former wetland degraded by the landward shift of the coastal dunes. Photos by: Massuanganhe, March 2011.

The back-barrier mangrove wetland is controlled by coastal dune barrier system. The morphology and the dynamics of the dune system is controlled by the prevailing southeasterly winds and longshore currents, factors that lead to regular morphological changes of the coastal dunes. Because of the predominant offshore winds, the coastal dunes shift landward (Fig. 4A) and cause degradation of wetland areas on the lee-side of the dunes. Cyclone and storm landfalls may disturb the migration pattern of the dunes, but they tend to be averaged with the more regular, inter-storm processes. This positive correlation between the delta geomorphology and climate is in agreement with studies on coastal dunes in e.g. Scotland and Brazil (McIlvenny et al., 2013; Zular et al., 2013).

There is a general understanding that deltaic wetlands are currently facing changes that will affect the coastal ecosystems negatively. In most of the recent studies, these changes are correlated with climate change and centered on the negative impacts (e.g. Wardekker et al., 2010; Cloern et al., 2011; Falcini et al., 2012; Fatorić and Chelleri, 2012). Certainly, taking into consideration the already ongoing climate-related processes in coastal environments, it is reasonable to discuss the impacts in this respect. Floods and cyclones are destructive climate events and they modify ecological systems and affect the socio-ecological systems negatively (Emanuel, 2005; Syvitski et al., 2009). The Save River delta is one of the examples in which tropical cyclones and floods affect negatively the mangrove ecosystem (Massuanganhe et al., 2015). However, extending the timescale we find that the landscape changes follow other long-term courses under interaction with global and local processes (e.g. sea-level, climate variability and rainfall pattern). If, on the one hand, ongoing global sea-level rise and compaction of recently deposited sediments are general problems that cause coastal flooding in river deltas (Syvitski et al., 2009), flooding on deltas due to high precipitation in the catchment area, on the other hand, induces higher sedimentation. In these examples, relative sea-level rise can be compensated by sedimentation, but both examples are considered to negatively impact on deltaic wetlands. It is a matter of time

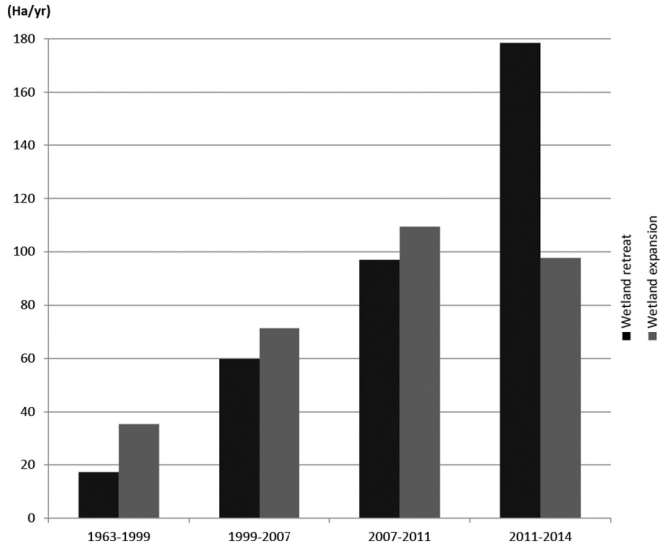

Fig. 5. Graph showing the changes of mangrove wetland in the selected study area between 1963 and 2014.

Table 1
Expanded and retreated wetland in the study over the time in analysis.

	Area (ha) (1963/4–1999)	Area (ha) (1999–2007)	Area (ha) (2007–2011)	Area (ha) (2011–2014)
Retreated wetland	617.76	478.89	387.67	535.35
Expanded wetland	1278.99	570.59	437.78	292.91
Total wetland gained	661.23	91.69	50.11	−242.45

perspective in which the phenomenon is seen. While large amounts of sediment deposition may result in vegetation burial on wetlands in the short term, it contributes to the construction of the deltaic platform, facilitating wetland development over longer timescales (Walsh and Nittrouer, 2004; Nittrouer et al., 2012; Nittrouer and Viparelli, 2014).

The interdecadal timescale evolution of the deltaic wetland of Save River occurs on the pre-existing platform in shallow water conditions. In shallow water, subaquatic and subaerial ridges are formed and evolve to other features, such as coastal dunes, thereby starting the morphodynamic process (Fig. 4). These processes are driven by geomorphological principles where erosion and sedimentation at various scales are evident, but with feedbacks from the biota. Analyzing our case study we find specific patterns of change in the wetland area, notwithstanding the short-term higher magnitude events such as cyclones and floods that can cause sudden drastic changes. The pattern of change in the study area is evidenced from the calculated changing rate and area (Fig. 5 and Table 1) which correlates with the physiographic patterns shown in Fig. 3. These rates and patterns are a response to the current combination of global and local factors that act over different timescales in the study area. Other examples of deltas (e.g. Atchafalaya Delta, Danube Delta and Godavari Delta) show a consistent interdecadal evolution pattern (Giosan, 2005; Rao, 2005; Olariu and Bhattacharya, 2006) and in some of these examples the changes occur within the deltaic wetland. Yet, the consistency of changes presented in our study agrees with the interpretations by McBride and Byrnes (1997) on the coastal landscape changes of coastal barriers in the Gulf of Mexico, where they noticed that consistent trends were visible for assessments undertaken over a minimum time interval of 25 years.

From our case study we observed that the feedbacks of the biota to the evolution of the deltaic wetland are evidenced by the positive correlation between the fine grained deposition and the expansion of deltaic wetland. This interdependence is reinforced by other examples and models showing the role of vegetation on sedimentation and stabilization of the recently deposited sediments (Morris et al., 2002; Nardin and Edmonds, 2014). In some examples of biogeomorphological interactions within mangrove wetlands, burrowing crabs show preference for certain species of plants and create, in this way, an interdependence which influences the development of the landscape (Escapa et al., 2015).

6.1. Future trends of deltaic wetland development

Projecting future scenarios of deltaic wetlands is a challenge considering the multiple stressors that affect these landscapes. Reasonably, most of the numerical models used to predict the trends in such complex environments are limited to certain number of variables (D'Alpaos et al., 2006, 2007) and these models also usually concentrate on spatially limited areas. From a geomorphological perspective, the conceptual models based on the morphodynamic processes can explain future trends of landscape change in a certain area. However, given the fact that morphodynamic processes are influenced by regional and local factors, at the scale of deltaic wetlands each specific feature is expected to respond in variable ways to a number of factors. For example, the development of a spit is driven by longshore currents, but its growth is controlled by the sediment budget and by the specific wind direction at each site. In numerical models, each variable is, in practice, a submodel as it encompasses a number of parameters. For specific case studies, the change detection maps reflect the feedback of the geomorphological units to the averaged driving factors. Because of that reason, the geomorphological interpretation of change detection maps is a baseline to explain the future changes (McBride and Byrnes, 1997).

Most of the erosion that occurs in the river channels is often compensated by accretion in point bars and therefore, the combination of both processes can be seen as a renewal process of the wetland. Taking the example of our case study we notice that there is still a potential for morphodynamic processes and mangrove colonization in sectors of the wetland. However, the opposite trend on the wetland expansion is an indication of possible change in the direction in which mangrove has been developing from between 1963/4 and 2011.

The generalized variation of the regional factors such as the reduction of sediment load to the deltaic systems might not be a linear factor that negatively affects the future changes of the deltas. Some rivers, are still discharging high amount of sediments under influence of high precipitation (Jones et al., 1993; Sidi et al., 2003; Falcini et al., 2012). During the flooding events the river system transports sediments in bed load and suspension (Milliman and Farnsworth, 2011) and the suspended sediments will not necessarily be trapped in dams. Looking to these examples and to our case study we recognize the reduction of bed load sediments due to the damming and other human activities in the catchment. However, we interpret that the future of the deltaic wetland systems is primarily dependent on the specificity of each river systems that include the climatic conditions in the catchment, sediment availability and the coastal processes.

7. Summary and conclusions

Like many other deltas, the Save River delta experiences landscape changes with particular emphasis on the wetland area. Over the last 50 years, some sectors of the wetland have been eroded and other sectors have been covered by dune sand, causing negative effects on the mangrove ecosystem. On the other hand, the mangrove wetland expanded and colonized new areas previously occupied by water. Both changes followed a consistent pattern characterized by a general increasing rate of both wetland expansion and wetland retreat over time, notwithstanding the inflection of the retreat trend between 2011 and 2014. The landscape changes registered in the study area are primarily related to morphodynamic processes and influenced by feedbacks from the biota. The morphodynamic processes interpreted in the case study reveal the result of the combination of global environmental factors acting on the river catchment, interacting with regional and local processes. Hence, each deltaic wetland will show a specific response depending on the specific settings of the river system.

Scale is an important factor to consider when assessing the evolution of wetland systems. Some of the high magnitude weather and climate-related events may impact negatively on the mangrove ecosystem causing rapid changes. However, the same events over a longer timescale are averaged-out in comparison with the long-term factors of landscape evolution, which may contribute positively to the development of mangrove ecosystem. Hence, the environmental changes that occur over interdecadal timescale in deltas can be assumed as part of the evolution process. The changing pattern constitutes a baseline with which to understand future trends in landscape evolution. Furthermore, in light of biogeomorphological changes, the geomorphology is a potential tool to predict future trends of the mangrove ecosystem.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2018.08.037.

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